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Experimental Validation of Channel Bowing Effects on Pin Power Distributions in a Westinghouse SVEA-96+ Assembly

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Effects of channel bowing on the pin power and ²³⁸U capture rate distributions have been studied experimentally and analytically in a test zone consisting of 9 full-size Westinghouse Atom SVEA-96+ fuel assemblies in the PROTEUS critical facility. A very significant bowing was simulated by displacing the central test assembly by ~9 mm in the two horizontal directions from its centred position in the 3×3 assemblies array. Calculations were performed for a whole-reactor model using the HELIOS and BOXER codes and for a reflected assembly using CASMO-4. The agreement between calculated and measured reaction rate distributions in this configuration is found to be of a quality similar to that for the case with the central assembly in its nominal position. The direct comparison of measured and calculated effects of the central assembly displacement on the reaction rate distributions (based on the results obtained in the two different LWR-PROTEUS configurations) confirms that, for a well-characterized displacement, the codes are capable of predicting the changes with high accuracy.

KEYWORDS: channel bowing, boiling water reactors, pin power distributions, integral experiments, assembly codes

I. Introduction

An interesting effect in the operation of BWR cores is the mechanical deformation of fuel assembly channels. This deformation during the irradiation of the fuel assemblies in the reactor, commonly referred to as channel bowing, is mainly due to variations of the fast-neutron fluence between the different sides of the assembly. The Zircaloy from which the channels are made grows under irradiation with fast neutrons due to the accumulation of point defects in the crystal lattice. Assemblies located near the periphery of the core experience a higher fast-neutron fluence on their sides oriented towards the centre of the core than on those closer to the outer edge. Therefore, the former walls grow more than the latter, causing the channel to bow towards the centre of the core. Another recently identified mechanism contributing to channel bowing is the so-called shadow corrosion, *i.e.* enhanced corrosion of the walls adjacent to a control blade inserted for a prolonged time.^{1,2)} Strongly bowed channels may interfere with the movement of control blades in the water gaps between the assemblies. In some cases, this has necessitated a redesign of core loading patterns,¹⁾ channel bowing having to be mitigated by shuffling assemblies exposed to a significant fast-flux gradient to locations with a reversed gradient (relative to the assembly concerned) in a subsequent cycle.

Channel bowing, even by small amounts which do not cause interference with the control blades, affects some important parameters for the operation of BWR cores. From the point of view of lattice physics, channel bowing means that

the widths of the inter-assembly water gaps are changed (smaller than nominal on one assembly side and larger on the opposite side). This change affects the neutron moderation conditions particularly for peripheral pins and, as a consequence, the neutron spectrum and the power in these pins. The pin-by-pin power distribution in its turn has an important effect on the thermal limits, particularly the critical power ratio (CPR). As shown for example in Ref. 2), a bowing of a few mm increases the peak pin power noticeably, mostly for assemblies in which the highest pin powers are found at the periphery (which is typical of fresh assemblies in their first cycle of irradiation). Channel bowing thus introduces additional uncertainties in the prediction of local power distributions. A precise characterization of channel bowing effects is therefore important with regard to the operation of BWRs. The purpose of the current paper is to describe a first-of-its-kind experimental validation of calculated channel bowing effects for modern 10×10 BWR fuel. The measurements were carried out in the framework of the LWR-PROTEUS programme at the Paul Scherrer Institute (PSI) in Switzerland.

II. The LWR-PROTEUS Phase I Experiments

One of the most significant, recent experimental programmes for the validation of assembly code predictions for modern LWR fuel assemblies is LWR-PROTEUS, a R&D collaboration between the Swiss Nuclear Utilities and PSI.³⁾ The goal of LWR-PROTEUS Phase I has been the validation of neutron transport codes such as CASMO-4, HELIOS, BOXER, PHOENIX and MCNP in the prediction of reactor physics parameters such as rod-by-rod reac-

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Fig. 1 LWR-PROTEUS core 7A test zone with a displaced central SVEA-96+ assembly and 8 surrounding assemblies in regular arrangement (only regions adjacent to central assembly shown)

tion rate distributions and reactivity effects that have been measured in an actual Westinghouse SVEA-96+ BWR assembly. The purpose of using actual fuel assemblies is to gain realism and to directly address specific uncertainties, including the effects of manufacturing tolerances and departures from nominal conditions, during the validation process itself.

The LWR-PROTEUS reactor configuration is essentially a coupled system. The central test region is surrounded by outer radial zones (the buffer, the D₂O-driver, the graphite-driver and a graphite reflector) which govern the criticality of the reactor, thus allowing experiments for a wide range of test lattice conditions.⁴⁾ In each of the Phase I configurations, an appropriate LWR neutron spectrum environment has been provided to a centrally-located SVEA-96+ fuel assembly in which measurements are carried out (the *test element*). The test element is surrounded by 8 other identical assemblies (see **Fig. 1**), the 3×3 arrangement (the *test zone*) being located inside an aluminium test tank. Since the elements are 4.5 m in length and the active height of the PROTEUS driver regions is about 1 m, the test tank can be moved axially to enable step-wise investigations in the different axial zones of the test assemblies.

A SVEA-96+ fuel assembly comprises 96 fuel rods arranged in four separate subbundles, each containing 24 rods on a square pitch around a central water canal (see **Fig. 1**). The ²³⁵U enrichment varies both axially and radially in the range 2–5% and some rods contain, additionally, gadolinia as an integral burnable absorber. The integral experiments performed have covered the most important features of the SVEA-96+ design, namely:

- Assembly radial heterogeneities: Geometrically-complex bypass regions, a relatively large number of burnable absorber fuel rods, heterogeneous ²³⁵U-enrichment distribution, *etc.*
- Assembly axial heterogeneities: Axial regions with differ-

ent average ²³⁵U-enrichment and materials distributions, spacers, studies related to part-length rods, *etc.*

- Core heterogeneities: Presence of fully- and partly-inserted absorber blades, channel bowing, and corresponding effects on instrumentation response.

Experiments were performed for full-density water moderation and for simulated partial voiding (using plastic inserts in a dry test zone). The results of various investigations related to the inherent assembly heterogeneities as well as to the effect of a fully-inserted absorber blade have been published previously.^{5–8)}

III. Measurements of Channel Bowing Effects

Channel bowing was simulated in LWR-PROTEUS by displacing the central test assembly from its regular position in the test zone arrangement by approximately 9 mm in the two horizontal directions, as shown in **Fig. 1**. Special upper and lower grids were used in this configuration, which is called LWR-PROTEUS core 7A. The displacement means that the nominal inter-assembly gaps (13.8 mm on all four sides) were changed to two narrow gaps of ~5 mm on the south and east sides and two wide gaps of ~23 mm at the north and west sides. This rather large movement of the central assembly was selected in order to emphasize the moderation condition changes, thus constituting an upper bound (typical bowings involve departures from the nominal gap of 2–3 mm). It also assured well-measurable effects that clearly exceeded uncertainties in the measurements, such as those due to counting statistics or to possible deviations of the assembly geometry from nominal dimensions. The investigations were performed for the lower part of the SVEA-96+ assemblies (average ²³⁵U enrichment of 4.02%) under full-density water moderation. The comparison of data measured in core 7A with those obtained in the corresponding configuration in which the test element was well centred

in the test zone (core 1A, see Ref. 6)) allows a direct experimental assessment of the effects of channel bowing.

The distributions of the total fission rate (F_{tot}) and of the ^{238}U capture rate (C_8) were determined by γ -ray scanning of 64 different fuel pins (out of a total number of 96). The experimental methods and procedures used were the same as those applied for other LWR-PROTEUS cores, which were described in detail *e.g.* in Ref. 5). After 1 h of irradiation at a reactor power of 30 W, the selected pins (10 per batch) were transferred to the automatic γ -scanner and counted repeatedly (one pin at a time) during about 18 h. The γ -ray spectra were measured using two horizontally opposed germanium detectors. From these spectra, four γ lines of different fission product nuclides (with suitable half-lives, intensities and separation from interfering lines) and one of ^{239}Np (for the C_8 distribution) were identified, the background continuum subtracted, peak areas deconvoluted, and the results processed into maps of relative reaction rates per pin.

The statistical uncertainties of the reaction rate distributions were derived from the conventional analysis of count rates, detector dead-times, *etc.*, as also from the weighted averaging of results from the different photopeaks used for obtaining the F_{tot} distributions. The average 1σ statistical errors associated with gamma-ray counting were 0.48% for F_{tot} and 0.54% for C_8 , with values for individual pins in the ranges 0.36 to 0.96% and 0.41 to 1.22%, respectively. These small uncertainties allow one to clearly identify calculational trends and biases of a few percent.

The fuel rod arrangement in the SVEA-96+ element is symmetric with respect to the northwest-southeast diagonal. Ratios of reaction rates measured for symmetrical positions are thus expected to be very close to unity. The diagonal symmetries obtained in the current measurements were indeed good, the mean of the ratios obtained for the 21 different pairs of corresponding fuel rods being 0.9998 and 0.9948 for F_{tot} and C_8 , respectively. The standard deviations of the ratios for an individual pin pair for the two reaction rates are 1.0 and 0.7%, and are thus comparable to those to be expected from the statistical uncertainties on the individual pin values.

IV. Codes and Models Used for the Calculations

Calculations were performed using the CASMO-4,⁹⁾ HELIOS¹⁰⁾ and BOXER¹¹⁾ codes. CASMO-4 is a well-known LWR assembly code developed by Studsvik Scandpower Inc. An important feature of CASMO-4 is the characteristics method used for the solution of the transport equation in two dimensions, which allows an explicit modelling of the fuel pins without cell homogenization. However, its capabilities are essentially limited to the calculation of single assemblies with reflective boundary conditions. CASMO-4 version 1.28.05H and the J2LIB cross-section library, based on JEF-2.2 nuclear data, were used for the present calculations. HELIOS is a modern lattice code (from Studsvik Scandpower Inc.) which is distinguishable from previous-generation codes mainly due to its great geometrical flexibility. The system to be calculated is built-up from heterogeneous space elements, inside each of which collision probabil-

ity methods are used to compute out-currents and fluxes. The space elements are coupled by interface currents. HELIOS version 1.6 and its 45-group library, based on ENDF/B-VI nuclear data, were used for the calculations reported here. BOXER is an LWR assembly code developed at PSI. It performs cell and two-dimensional transport and depletion calculations in cartesian geometry. The cross-section library is based mainly on JEF-1, except for ^{155}Gd and Zircaloy, nuclear data for the latter being taken from JENDL-2 and ENDF/B-IV, respectively. The two-dimensional transport calculations are performed by means of a transmission probability integral transport method in x - y geometry for homogenized cells, using first-order spherical harmonics expansions for the mesh surface currents and a linear space dependence for the surface currents and for the source within the meshes.

In all the calculations, care was taken to model the actual geometry of the test zone as accurately as possible. In particular, values measured in the PROTEUS core configuration were used for the gaps between the central test element and its four neighbours (these were not perfectly symmetric relative to the diagonal), as well as for the position of the pins within the assembly. The enrichments of the fuel pins used in the calculations were measured values as reported in the fuel manufacturer's quality control documentation.

The reaction rate distributions for comparison against the PROTEUS measurements were obtained from calculations using two-dimensional models of a horizontal section through the whole PROTEUS reactor with HELIOS and BOXER, and from a reflected-assembly model with CASMO-4. The HELIOS model uses a detailed description of all the radial regions up to the outer edge of the graphite reflector. The test zone was modelled consistently with the options used at the utility for fuel management and core follow calculations. In the UO_2 pins, the fuel was divided into two radial zones, a thin ring near the periphery and the remainder of the pellet. For the Gd-poisoned pins 5 equivo-lumic radial zones were used. The moderator in all the pin cells was subdivided into 8 sectors, and an extra radial region was introduced in the moderator of the Gd-pin cells near the pin surface. The angular distribution of the currents at the interfaces between the space elements throughout the configuration was approximated by using four azimuthal sectors on each side of the interface, a cosine current distribution being assumed inside each sector (so-called "coupling order" 4 in HELIOS). The calculations were carried out in the full library group structure, *i.e.* 45 groups. In the case of BOXER, the horizontal cross-section of the reactor at the mid-plane was approximated in x - y geometry. In the test zone, each pin cell was represented explicitly. A refined and somewhat irregular mesh grid had to be used to represent the cell boundaries both in the displaced central element and in the outer 8 assemblies. The modelling for the outer zones of the reactor was simplified with, in particular, the circular zone boundaries being replaced by square boundaries enclosing the same cross-sectional area. The pin cells were modelled using a single radial zone in the fuel for the UO_2 pins and four zones, all having the same volume, in the Gd-poisoned pins. A 24 energy-group structure com-

prising a rather large number of groups in the high ($E > 300$ keV) and thermal energy ranges was used for the two-dimensional transport calculations. The radial description of both the HELIOS and BOXER models corresponded to the actual, as-built critical configuration of core 7A, including the measured critical graphite-driver loading. The zone-independent axial buckling was adjusted in each case to achieve the critical condition ($k_{eff}=1$).

CASMO-4 calculations were carried out for the central test assembly with reflective boundary conditions in the middle of the water gaps between this assembly and its four nearest neighbours. The 2×2 assemblies model with periodic boundary conditions as used in Ref. 2) for a calculational study of the effects of channel bowing is not applicable to the configuration considered here, because the central assembly was displaced beyond the mid-planes of the gaps between the neighbouring assemblies (in regular position). In addition, with the CASMO-4 version used, multi-bundle calculations cannot be performed using the characteristics method. The calculations were performed in a manner representative of production calculations using standard modelling options as far as possible. In the UO_2 pins, the fuel was represented by a single radial zone, whereas the Gd-poisoned pins were automatically subdivided by the code into 10 radial zones of equal cross-sectional areas. The default azimuthal mesh was used in the pin cells, *i.e.* 4 sectors in the pins and 8 regions in the moderator. The quadrature sets used for the characteristics calculation were also the default ones, with a track spacing of 1 mm for the thermal energy groups and 4 mm in the epithermal and fast ranges. Eight energy groups were used for the two-dimensional transport calculation. The resulting reaction rate distributions were converted to the actual PROTEUS situation using correction factors computed as the ratios of the respective quantities from whole-reactor and reflected-assembly BOXER calculations. The same mesh grid in the test assembly was used in the latter two calculations in order to obtain correction factors which are not biased by numerical effects of mesh size. The corrections are relatively substantial at the corners for which, in particular, moderation conditions (more specifically, the quantity of water in the adjacent inter-assembly gaps) cannot be adequately represented in the reflected-assembly model. In the interior of the assembly, the corrections amount only to a few percent and vary smoothly, representing the global radial flux curvature in the finite test zone. The comparison of the reflected-assembly results obtained using CASMO-4 with experimental data thus has to rely significantly on the correction factors from BOXER. However, inaccuracies in BOXER can be expected to affect results for both the reflected-assembly and whole-reactor calculations in a similar manner, so that the quality of the correction factors should be much better than that of the results for the individual models. The same kind of correction factors can also be determined from the reaction rate distributions obtained using the whole-reactor and reflected-assembly HELIOS models. The results of the two codes are in close agreement with RMS differences of 0.5 and 0.4% for the corrections for the F_{tot} and C_8 distributions, respectively. The comparison of HELIOS and BOXER values confirms

the adequacy of the correction factors used and indicates that their uncertainty is small.

V. Comparison of Calculated and Experimental Results

1. Reaction Rate Distributions

Both experimental (E) and calculated (C) pin-by-pin distributions were first normalized to the same average value for the 64 measured pins. The thus normalized C and E values were then compared in terms of C/E ratios for the total fission rate and the ^{238}U capture rate in each measured pin. In these comparisons, it should be borne in mind that the experimental statistical uncertainties (1σ) are typically 0.5% for both F_{tot} and C_8 .

The detailed pin-by-pin distributions of C/E ratios are shown in Fig. 2 for F_{tot} and in Fig. 3 for C_8 . The root-mean-square (RMS) deviations of the C/E values from unity, as also the maximum and minimum C/E values, are given in Table 1. The results generally indicate a good agreement between the calculated and measured values. The RMS and maximum deviations are comparable to those observed previously for other LWR-PROTEUS experiments.^{5,6)} The agreement of the BOXER results with the measured data actually appears to be somewhat better than that for regular inter-assembly gaps,⁶⁾ whereas the deviations of the HELIOS and CASMO-4 results are slightly larger. In the case of BOXER, the apparent improvement has been shown to be related to the refined mesh grid imposed by the superposition of cell boundaries in the regular and displaced assembly positions in the core 7A model.

Some trends can be observed in Figs. 2 and 3. The most

Fig. 2 C/E values for the pin-by-pin total fission rate as obtained with CASMO-4 (upper values), HELIOS (middle values) and BOXER (lower values)

Shaded squares represent Gd-poisoned pins.

Fig. 3 C/E values for the pin-by-pin ^{238}U capture rate as obtained with CASMO-4 (upper values), HELIOS (middle values) and BOXER (lower values)
Shaded squares represent Gd-poisoned pins.

Table 1 Statistics of C/E distributions for pin-by-pin total fission and ^{238}U capture rates, as obtained for LWR-PROTEUS core 7A with CASMO-4, HELIOS and BOXER

Reaction	Code	RMS (%)	Maximum	Minimum
F_{tot}	CASMO-4	1.2	1.028	0.965
	HELIOS	1.4	1.023	0.959
	BOXER	1.4	1.023	0.967
C_8	CASMO-4	1.3	1.024	0.972
	HELIOS	1.2	1.028	0.962
	BOXER	1.1	1.025	0.963

conspicuous deviation is a systematic underprediction of the total fission rate in the Gd-poisoned pins by approximately 2% on the average with CASMO-4 and BOXER, and ~3% in the case of HELIOS. BOXER tends to overpredict F_{tot} somewhat in the corner pins and to underpredict it in UO_2 pins with two burnable absorber (BA) neighbours, such as pins I2, C7 and H7. HELIOS shows a trend in the opposite direction, *i.e.* a 1 to 2% higher calculated F_{tot} than experiment for UO_2 pins with two nearest Gd neighbours. For the ^{238}U capture rate, a concentration of slightly high C/E ratios can be seen in the peripheral pins adjacent to the wide water gaps (row J and column 10) for all the three codes, whereas low values are found in the pins surrounding the central water canal. There is no systematic effect for C_8 in the BA pins. These trends have been observed consistently in all the LWR-PROTEUS configurations with full-density water moderation, both for the regular test-zone arrays with the test element in its centred position and for cases with an inserted control blade.^{5,6,8} They can, therefore, be considered as systematic deviations of the respective codes and

have nothing to do with the displacement of the central test element. Several conceivable causes for the underprediction of F_{tot} in the Gd-poisoned pins, such as nuclear data of Gd, the geometrical modelling of the pellets or the granular structure of the UO_2 - Gd_2O_3 fuel, have been studied, but no plausible explanation for a deviation of the observed magnitude has been found.

In the present configuration with a displaced central assembly, it is of particular interest to check for spatial trends of the C/E ratios in the direction of the displacement, *i.e.* diagonally from northwest to southeast. To facilitate this investigation, average C/E values have been computed for each of the four subbundles. These are given in Fig. 4. The results show that there is a slight tilt for both reactions and all three codes, with a higher average C/E in the northwest subbundle, adjacent to the two wide gaps, than in the southeast, near the narrow gaps (note that the average C/E over the whole assembly is not equal to 1.0, because the normalization used assures only that the average difference of measured and calculated values, *i.e.* $C-E$, is zero). These averages confirm a trend which can also be inferred, although less clearly, from the C/E ratios for the individual pins, especially from the concentration of values less than unity at the south and east edges. The tilt is more pronounced for C_8 than for F_{tot} . The smallest differences between the averages in these two subbundles are found for both reactions with HELIOS, and the largest ones with CASMO-4. These differences are, in all cases, greater than those to be expected from the experimental statistical uncertainties (for these averages, they are about 1/4 of the values for a single pin, *i.e.* in the range 0.10 to 0.15%).

A somewhat less significant trend can also be observed in the other diagonal direction (northeast–southwest), especially for C_8 , although (from symmetry considerations) one would expect no difference to occur. Close examination of the results has shown this tilt to be due to a larger asymmetry in the measured values than in the calculated ones.

2. Effects of Channel Bowing

The capabilities of the lattice codes in predicting the effects of the displacement of the central assembly (or of channel bowing) can be assessed directly by comparing the results for LWR-PROTEUS cores 1A (test element centred, see Ref. 6)) and 7A (currently studied configuration, test element displaced). For this purpose, ratios of both measured and calculated reaction rate values between the two configurations were determined for those pins which were investigated in both cases (a few more pins were measured in core 7A than in core 1A), each of the reaction rate distributions being renormalized to an average of unity in this common subset.

Before discussing the pin-wise C/E values for the channel-bowing effects on F_{tot} and C_8 , it is useful to first consider the magnitude of the changes themselves. Thus, pins adjacent to the wide water gaps have higher values for both reaction rates in the case of the displaced element, lower values being found for pins near the narrow gaps. The maximum changes due to the currently considered, large displacement of 9 mm are approximately 16% for F_{tot} and 6%

F_{tot}		C_8	
CASMO-4		CASMO-4	
1.002	1.000	1.010	1.002
0.996	0.995	0.994	0.990
HELIOS		HELIOS	
0.998	1.000	1.005	1.004
0.998	0.996	0.996	0.994
BOXER		BOXER	
0.999	0.999	1.007	1.004
0.995	0.995	0.994	0.994

Fig. 4 Average C/E values in the four subbundles for the total fission rate (left column) and the ^{238}U capture rate (right column)

for C_8 , these being found typically in peripheral pins near the middle of the sides of the assembly. The latter observation may contradict the intuitive assumption that the largest changes should be found for the corner pins. However, looking at the situation more carefully, one can easily see that the corner pins experience a less drastic change in moderation than those in the middle of the sides (for example, the narrow-narrow corner pin is still influenced by a relatively large quantity of water in the unchanged gaps between the outer assemblies, *cf.* Fig. 1).

For the calculation/experiment comparison of pin-wise channel bowing effects, the BOXER values for core 1A were taken from a calculation for a reflected assembly in which each pin cell was evenly divided into 2×2 meshes, and corrected for the global flux shape in the LWR-PROTEUS test zone by multiplying with the ratios of BOXER results from whole-reactor and reflected-assembly models (with one mesh per pin cell). This was done in order to obtain a consistent comparison with the core 7A results, separating the effect of the displacement from numerical effects of the mesh widths (in test calculations, effects of mesh refinement up to $\sim 1.5\%$ on the F_{tot} distribution were found, whereas differences between 2×2 equal meshes per pin cell and the grid used for core 7A were negligible). In the case of HELIOS, the ratios between results for the two cores were determined while consistently using version 1.6 for both configurations, whereas the C/E comparison for core 1A described in Ref. 6) was based on results of version 1.4. In addition to employing a more recent code version, the modelling was also somewhat refined in the new calculations. The CASMO-4 results were converted to the actual LWR-PROTEUS situation using appropriate correction factors from BOXER calculations for each of the cores.

C/E ratios for the pin-wise changes of the reaction rates between the two configurations (*i.e.* for the channel bowing effects) are shown for F_{tot} and C_8 in Figs. 5 and 6, respectively. The corresponding RMS and maximum C/E deviations are given in Table 2. The statistical uncertainties of

Fig. 5 C/E values for channel bowing effects on the pin-by-pin total fission rate, as obtained with CASMO-4 (upper values), HELIOS (middle values) and BOXER (lower values). Shaded squares represent Gd-poisoned pins.

Fig. 6 C/E values for channel bowing effects on the pin-by-pin ^{238}U capture rate, as obtained with CASMO-4 (upper values), HELIOS (middle values) and BOXER (lower values). Shaded squares represent Gd-poisoned pins.

the measured ratios are determined by the combination of the errors of the two measurements and amount to typically 0.7% for F_{tot} and 0.9% for C_8 . Generally, it can be seen that all the codes predict the impact of channel bowing on the reaction rate distributions with good accuracy. The RMS deviations are only slightly larger than the uncertainties of the

Table 2 Statistics of C/E distributions for channel bowing effects, viz. for pin-by-pin reaction rate ratios between cores 7A and 1A, as obtained with CASMO-4, HELIOS and BOXER

Reaction	Code	RMS (%)	Maximum	Minimum
F_{tot}	CASMO-4	1.1	1.021	0.973
	HELIOS	1.1	1.023	0.975
	BOXER	1.2	1.022	0.971
C_8	CASMO-4	1.7	1.037	0.965
	HELIOS	1.4	1.028	0.966
	BOXER	1.4	1.027	0.965

F_{tot}		C_8	
CASMO-4		CASMO-4	
1.006	1.002	1.013	1.005
0.995	0.995	0.992	0.991
HELIOS		HELIOS	
1.002	1.001	1.007	1.005
0.996	0.997	0.993	0.997
BOXER		BOXER	
1.003	1.002	1.008	1.005
0.995	0.998	0.992	0.997

Fig. 7 Average C/E values in the four subbundles for channel bowing effects on the total fission rate (left column) and the ^{238}U capture rate (right column)

measured values, particularly for F_{tot} . For both reactions and all three codes, there are more C/E values above than below unity in the northwest diagonal half of the assembly, values below unity being more concentrated in the southeast part, especially in the peripheral rows. This suggests that the C/E values investigated here, viz. those for the reaction rate ratios between the two different configurations, have a similar tilt in the diagonal direction as for the displaced-assembly reaction rate distributions themselves. As before, the trend can be viewed more clearly by considering average C/E values for the subbundles. These are shown in **Fig. 7** (in analogy to **Fig. 4**). They confirm that there is a slight tilt in the northwest–southeast direction, indicating that the calculations tend to exaggerate somewhat the effect of channel bowing. This means that all the codes used produce slightly conservative results for the increase of the local power peaking factor due to channel bowing. The implications of this trend for in-core fuel management are, however, dependent on the specific characteristics of each reactor and on the core loading strategy used. The differences of the subbundle averages are comparable to those discussed earlier, i.e. those found for the reaction rates in core 7A. The trend is more pronounced for C_8 than for F_{tot} , and stronger in the CASMO-4 results than in those obtained with the other two codes. For the F_{tot} ratios, the stronger tilt in the CASMO-4 re-

sults seems to be related to the energy group structure used for the two-dimensional transport calculation. In test calculations, the average C/E values in the northwest and southeast subbundles were found to approach the HELIOS and BOXER results with an increasing number of groups. For the C_8 ratios, however, the trend remains stronger than that found with the other two codes for every group structure used.

A slight tilt in the northeast–southwest direction, with higher average C/E values in the northeast, can also be noted. The differences are again similar to those for the displaced-assembly reaction rates. As in the latter case, the trend is stronger for C_8 than for F_{tot} , and reflects a slight asymmetry in the experimental values which cannot be found in the calculational results.

VI. Conclusions

Channel bowing effects on the total fission and ^{238}U capture rate distributions have been studied experimentally and analytically in the framework of the LWR-PROTEUS Phase I programme. A very significant bowing (~ 9 mm) has been simulated by displacing the central test assembly from its nominal position in a test zone of 9 Westinghouse Atom SVEA-96+ fuel assemblies under full-density water moderation. This rather large displacement was selected in order to produce significant effects clearly exceeding experimental uncertainties.

The calculations performed using the CASMO-4, HELIOS and BOXER codes show that the effects of channel bowing on the pin power and ^{238}U capture distributions are predictable quite accurately. The quality of the C/E comparisons is not inferior to the case where the central assembly was placed in a nominally regular arrangement. A direct comparison between the LWR-PROTEUS configurations with the central assembly in the two different positions also shows that the changes of these reaction rates due to a well-characterized displacement of the assembly are calculated accurately. These findings, together with geometrical data on channel bowing in actual operating BWR cores, could possibly lead to a reduction of corresponding penalties imposed on the maximum reactor power.

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